The Next Generation of Spaceborne Radars for Cloud and Precipitation Measurements

Eastwood Im*, Eva Peral, Mauricio Sanchez-Barbetty, Simone Tanelli

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
**Corresponding Author: eastwood.im@jpl.nasa.gov*

Keywords: cloud, precipitation, Doppler, microsatellite, nanosatellite.

Abstract

NASA's Earth Science Technology Office (ESTO) is currently developing advanced instrument concepts and technologies for the next generation of spaceborne atmospheric radars for clouds and precipitation measurements. Two representative examples are the *Radar in a CubeSat* (RainCube) – a miniaturized Ka-band precipitation intensity profiling radar for operation on a 6U CubeSat bus; and the *Multi-Application Smallsat Tri-band Radar* (MASTR) – a Ku/Ka/W band, electronic scanning, and Doppler atmospheric radar. These radar concepts will be capable of providing information on both the state and the process of the atmospheric water (as opposed to just the state information provided by existing spaceborne radars) to fill the current observational gaps in the advancement of weather and climate models.

1 Introduction

Cloud and precipitation processes are the key drivers defining severe weather, energy transfer, pollution transport, and atmospheric climate feedbacks. Processes here refer to the various physical mechanisms within clouds that act to produce precipitation. In a changing climate it becomes essential to understand at both the local and global scale the underlying cloud processes (via measurable proxies) that result in precipitation such that these can be incorporated into the next generation of climate and numerical weather prediction (NWP) models. In the next decade as the resolution of these climate models increase to explicitly represent cloud and convective processes, it is equally imperative to plan for timely observations that can constrain and define these processes to produce more accurate predictions of the water cycle at both the weather and climate timescales.

As such the cloud and precipitation processes have been identified as one of the targeted measurements for the next generation of spaceborne radar observing missions [1, 2, 3]. The key departure with respect to predecessor missions (e.g., TRMM [4], CloudSat [5], GPM [6]) is the need to capture atmospheric processes of a rapidly evolving, dynamic nature. To achieve this objective, three broad categories of measurement capabilities have been explored and proposed: 1) Ku/Ka/W-band tri-frequency operations for simultaneous acquisition of radar backscatters from both cloud and precipitation targets; 2) Doppler measurements that directly observe the instantaneous velocity of the clouds and precipitation targets; and 3) rapid revisit (i.e., at the cloud temporal scale, minutes to tens of minutes) approaches to capture the evolution of the process at sufficient resolution.

In the last decade, telecommunications and military applications have steadily expanded to the upper part of the spectrum of radar frequencies. This has resulted in significant progress in the areas of RF power amplification and deployable antennas at sub-cm wavelengths. These advances, together with the advances in digital technology, signal processing, and small satellite technologies, has substantially improve the implementation feasibility of the next generation of spaceborne radar instruments for cloud and precipitation measurements.

By taking advantage of these technology advancements and leveraging the TRMM, CloudSat, and GPM experience, ESTO has recently developed a number of instrument concepts for the next generation of spaceborne atmospheric radars for clouds and precipitation measurements. For example, the flight technology validation mission of a nanosatellite-class atmospheric profiling radar called Radar in a CubeSat (RainCube) to address targeted atmospheric science questions in a rapid and affordable manner is now being developed by ESTO. RainCube is a Ka-band vertical profiling radar operating on a 6U CubeSat platform. The success in the low-cost and miniaturized RainCube instrument development will demonstrate the feasibility of future constellation-based Earth science observations for improved spatial and temporal coverage not previously affordable with traditional spacecraft.

Concurrently, ESTO is developing an airborne prototype of the *Multi-Application Smallsat Tri-band Radar* (MASTR) capable of providing polarimetric and Doppler measurements of cloud and precipitation at Ku-, Ka- and W-band simultaneously and at large cross-track swath. MASTR is intended to fill the current observational gaps in the advancement of weather and climate models by providing information on both the states and the processes of atmospheric water that govern model physics and prediction skill.

This paper will provide an overview of these two emerging radar concepts, as well as the critical enabling technologies behind them.

2 Radar in a CubeSat (RainCube)

RainCube (Radar in a CubeSat) is a 6U CubeSat mission currently developed by the Jet Propulsion Laboratory (JPL) with funding supports from ESTO. The objective of the mission is to develop, launch, and operate a 35.75 GHz precipitation profiling radar payload to validate a new architecture for Ka-band radars and an ultra-compact deployable Ka-band antenna design in the space environment. The baseline instrument configuration is a fixed nadir-pointing profiling radar at Ka-band with a minimum detectable reflectivity factor better than +20 dBZ (CBE 11dBZ) at 250m range resolution. The footprint size (i.e., horizontal resolution) is determined by the antenna size. For a nominal orbital altitude of 400 km, the RainCube antenna produces approximately an 8.5 km footprint.

Radar instruments are typically not suitable for small satellite platforms due to their large size, weight, and power consumption (SWaP), but recently a novel architecture for a Ka-band radar has been developed at JPL which reduces these resource requirements by over an order of magnitude with respect to the existing spaceborne radars and is compatible with the capabilities of low-cost satellite platforms such as SmallSats or CubeSats. The key enabler to reduce SWaP is the modulation technique: offset IQ (in-phase and quadrature) with pulse compression. Pulse compression is used to achieve the required sensitivity with a custom amplifier fabricated with off-the-shelf GaAs solid-state pHEMT chips. The modulated pulse shape is optimally chosen to minimize the range sidelobes.

The digital subsystem consists of a single board that includes low power CMOS digital-to-analog conversion (DAC), analog-to-digital conversion (ADC), telemetry ADC chips providing 24 channels of telemetry, and a single commercial-grade flash-based FPGA performing all control, timing, and on-board processing (OBP). The radar OBP algorithm consists of data filtering, range compression, power computation and along-track averaging.

The RainCube antenna is a 0.5-meter mesh antenna that stows in 1.5U. It is optimized at 35.75 GHz with a measured gain of 42.6 dBi (over 50% efficiency). The antenna uses a Cassegrain architecture as it places the sub-reflector below the focal point of the antenna, allowing the antenna to stow in a tight volume. The mesh antenna surface is supported by 30 deep ribs, which provide high structural rigidity to stretch the mesh to a precise parabolic shape. The antenna deployment sequence is shown in Figure 1.

The flight model of the RainCube radar as shown in Figure 2 was completed and is currently being integrated into the spacecraft bus provided by Tyvak Nano-Satellite Systems, Inc. based on its Endeavour avionics platform technology. Integration and testing of the full RainCube vehicle, illustrated in Figure 3, is scheduled to be completed by the fall of 2017. Tyvak will deliver the assembled RainCube spacecraft to NanoRacks for integration into their 'doublewide' (2U x 6U) dispenser. The NanoRacks canisterized CubeSats will be delivered to the International Space Station (ISS) as soft-stowed cargo in the pressurized volume with one of the Station's resupply missions sometime in the Spring of 2018. RainCube and the other NanoRacks payloads expect to be deployed within a few months after arrival to the ISS. RainCube's in-orbit operations is planned to be 12 months.

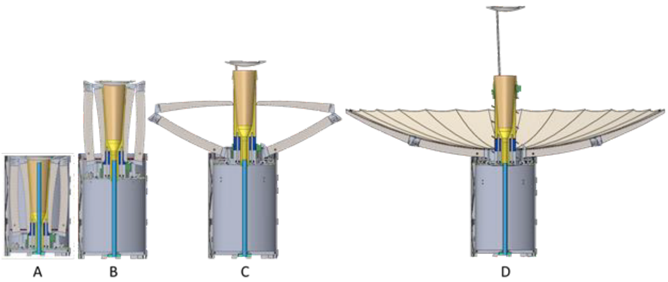

Figure 1: The RainCube antenna deployment sequence unfurls the 0.5m antenna from a 0.1m diameter cylinder.

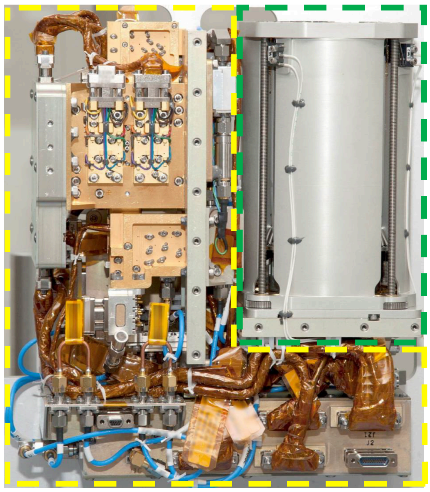

Figure 2: RainCube radar electronics (3U, yellow) and deployable antenna (1.5U, green) in flight packaging.

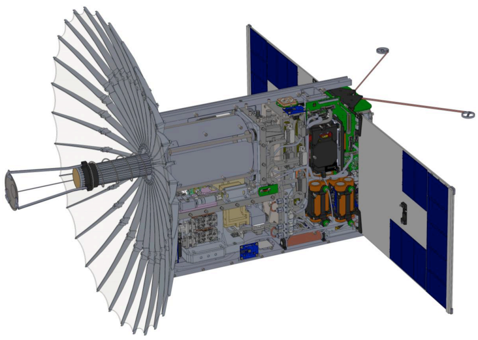

Figure 3: The RainCube 6U satellite.

3 Multi-Application Smallsat Tri-band Radar (MASTR)

JPL is also developing an airborne prototype of a new SmallSat instrument concept called MASTR capable of electronic scanning, Doppler velocity measurement, and polarimetry at Ku/Ka/W band frequencies. MASTR is composed of three subsystems: backend (BE, including digital, control, up and down conversion), frontend (FE, including RF active feeds and primary reflector), and power conditioning and thermal control (PTC). BE is based on the RainCube radar design described in Section 2 and will fit within a 2.5U volume. FE consists of a cylindrical parabolic antenna reflector with a set multi-band linear feed arrays. The PTC module for the airborne MASTR prototype is designed specifically for operating in the aircraft environment. The PTC subsystem design for the spaceborne MASTR would be unique and dependent on the actual flight environment. Regardless, the spaceborne PTC technology is mature and flight proven. MASTR was conceived to enable significantly smaller instruments that meet several science needs using a modularized architecture that is flexible and can adapt to multiple measurement objectives.

For MASTR, cross-track scanning at multiple frequency bands is enabled by the use of a set of three Active Linear Array Feeds (ALAFs), one at each of Ku, Ka and W band, in conjunction with an offset-fed parabolic cylindrical reflector. Together, these form the Advanced Cloud and Precipitation Radar Antenna (ACPRA, see Figure 4). The ACPRA takes advantage of the simplicity and high gain of the reflector and achieves agile electronic beam steering using the ALAF, which is oriented to scan across the direction of flight.

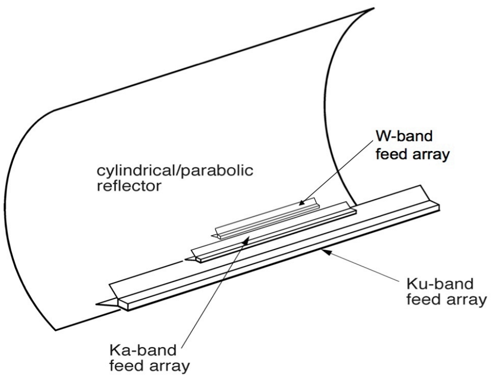

Figure 4: The ACPRA concept.

Of the three frequency bands, W-band is the most challenging, due to the very small array element spacing required and the difficulty of producing sufficient transmit power at these frequencies. However, through the ESTO support a joint research team from JPL, Raytheon and Nuvotronics, Inc. has recently developed a W-band Scanning Array Tile (SAT) and demonstrated wide-swath electronic beam steering capability. Figure 5 is a picture of fabricated W-band SAT which includes eight transmit channels and sixteen receive channels. This SAT is the building block of the MASTR W-band ALAF. Figure 6 demonstrates the electronic scanning of this 8x2 element SAT.

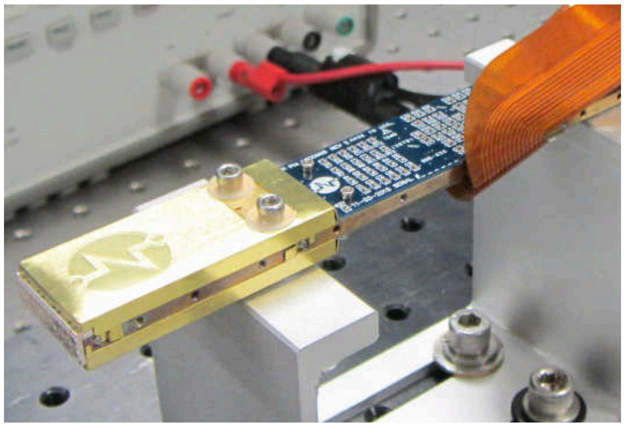

Figure 5: 8x2 element W-band SAT on test bench.

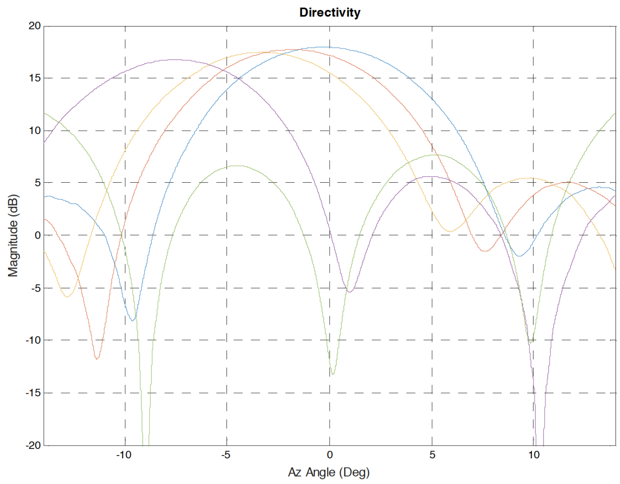

Figure 6: Electronically-scanned beam for W-band SAT.

Nuvotronics is currently developing Ku- and Ka-band SATs to complement the W-band SAT. The Ka-band SATs utilize the same microfabrication technology as the successfully-demonstrated W-band SAT, but the development are much less challenging given the less stringent loss requirements and the larger channel-to-channel spacings.

The airborne prototype development of MASTR is expected to take about 30 months. The engineering test flight on the NASA DC-8 aircraft has been planned for late summer of 2019. Table 1 summarizes the expected capabilities of the MASTR airborne prototype during DC-8 operations.

	Ku	Ka	W
Center Frequency (GHz)	13.4	35.6	95.1
Antenna Size (m)	0.5 x 0.3		
Beamwidth (deg)	3 x 5	1.1 x 1.9	0.4 x 0.7
Peak RF Power (W)	240	160	96
Bandwidth (MHz)	4	4	1
Pulse Length (μs)	10	10	5
Pulse Rep Interval (μs)	200	200	200
Max. Scan Angle (deg)	10	10	10
Meas. Sensitivity (dBZ)	-5	-10	-30
Doppler Precision (m/s)	0.3	0.2	0.2
Horizontal Res. (km)	0.7 x 0.9	0.3 x 0.5	0.2 x 0.3
Range Accuracy (m)	50	50	100

Table 1: Expected capabilities of the MASTR airborne prototype.

4 Summary

Owing to the immense success of the TRMM, CloudSat, and GPM atmospheric radars and with the rapid advancement of radar component and small satellite technologies in recent years, a number of new instrument ideas and concepts for the next generation spaceborne atmospheric radars have emerged. This paper describes two such new radar concepts, RainCube and MASTR, currently being developed by ESTO and JPL.

RainCube, the shoebox-size 6U CubeSat radar, is being planned for launch to and later release from ISS sometime in 2018. It will demonstrate vertical profiling of precipitation at sensitivities comparable to its predecessors (TRMM and GPM radars) that are two orders of magnitude larger in SWaP.

MASTR, currently being prototyped as an airborne radar, is designed to provide tri-frequency, polarimetric, and Doppler measurements of clouds and precipitation simultaneously. Such multi-parameter measurement sets will provide the missing information needed to improve our understanding of cloud processes and enable more accurate predictions of the water cycle at both the weather and climate timescales.

Acknowledgements

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology with funding support provided by the Earth Science Technology Office (ESTO), National Aeronautics and Space Administration (NASA).

References

[1] ACE Study Team. "ACE 2009-2015 Progress Report and Future Outlook", *NASA ACE Study Team Report*. http://dsm.gsfc.nasa.gov/ace/library.htm (2016).

[2] Z. S. Haddad, and co-authors. "Observing the dynamics of convection and severe weather analysis and forecasting", *White paper submitted in response to US NRC Earth Science Decadal Survey RFI2.* http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/15647/2604456/47-2c2c16abd13c32b54711c7cc48884c0f_HaddadZiadS.pdf.

[3] G. S. Jackson, et al. "Addressing Major Earth Science Challenges in Cloud and Precipitation Process Modeling", *White paper submitted in response to US NRC Earth Science Decadal Survey RFI2.* http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/15647/2604456/191-ffaec6c558eef6562cb12fb87d63329f_Skofronick-JacksonGail.pdf.

[4] C. Kummerow, et al. "The Tropical Rainfall Measuring Mission (TRMM) sensor package." *Journal of Atmospheric & Oceanic Technology*, **15.3** (1998).

[5] G. L. Stephens, et al. "CloudSat mission: Performance and early science after the first year of operation." *Journal of Geophysical Research: Atmospheres*, **113.D8**, pp. 1984–2012, (2008).

[6] K. Furukawa, et al. "Proto-flight test of the Dual-frequency Precipitation Radar for the Global Precipitation Measurement," *Proc. IEEE Intl. Geoscience and Remote Sensing Symposium (IGARSS)*, pp.1279,1282, 24-29 July 2011. doi: 10.1109/IGARSS.2011.6049433